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Review

Compression of Composite Materials: A Review

by
E. T. Camponeschi, Jr.

DTRC-87/050   Compression of Composite Materials: A Review

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This paper is a literature review of research on the compressive response of fiber-reinforced composite laminates. Emphasis is on recent research with papers from 1980 to the present included. The review is organized by subject and the papers are included in one of three main groups; COMPRESSION TEST METHODS, FAILURE THEORIES AND FAILURE MECHANISMS AND EXPERIMENTAL INVESTIGATIONS. Tables are presented that summarize the information included in the paper dealing with the evaluation of test methods and generation of experimental data. These tables provide an index for quick reference to the research discussed in this paper.

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ABSTRACT

This paper is a literature review of research on the compressive response of fiber-reinforced composite laminates. Emphasis is on recent research with papers from 1980 to the present included. The review is organized by subject and the papers are included in one of three main groups; COMPRESSION TEST METHODS, FAILURE THEORIES AND FAILURE MECHANISMS, AND EXPERIMENTAL INVESTIGATIONS. Tables are presented that summarize the information included in the papers dealing with the evaluation of test methods and generation of experimental data. These tables provide an index for quick reference to the research discussed in this paper.

ADMINISTRATIVE INFORMATION

INTRODUCTION

The compressive response of fiber-reinforced composite materials has been the subject of investigation since the development of these materials. Even with this long-term interest, this area is still one of the least understood in the field of composites today. Many factors influence the compressive response of composite materials and considered together or separately they can trigger a number of failure modes. These factors occur at the structural level (coupon geometry), the macrostructural level (lamina level), and the microstructural level (fiber-to-matrix level). On the microstructural level, the presence of local inhomogeneities and defects, which are difficult to characterize and model, influence the failure mechanisms that will dominate the response of a composite in compression more than in any other state of stress. Therefore, manufacturing plays a significant role in determining the compressive response of composite materials, and will play an even more significant role as the section thickness of composites increases. Constituent properties, laminate orientation, specimen geometry, method of load introduction, fiber waviness, voids, and stress concentrations all have been shown to play a role in determining the predominant failure mode governing compression failure. These failure modes include global Euler buckling, microbuckling, transverse tension, fiber kinking, fiber compression failures, matrix compression failures, or delamination.

The objective of this review paper is to present a summary of the recent research efforts that have concentrated on the compressive response of composite materials. The literature available in this area is voluminous, so the most recent work in the area (1980 to the present) was researched in the preparation of this document. This paper is still a thorough review of the compressive response of composites since important results of studies prior to 1980 are included in recent compression research efforts, and the early papers that have significantly influenced our current understanding are included here for completeness.

This paper is not organized chronologically, but rather by subject to provide an understanding of three often asked questions concerning compression response:

How should composite materials be tested in compression?
How do composite materials fail under a compressive load?
What compression data is available for composite materials?

Tables as well as text have been prepared to present this information in the most accessible manner.

Although the papers reviewed here help to answer the above three questions, a more important question that is often overlooked in papers dealing with compression is **What is compression failure strength?** Unlike isotropic materials, for composites this becomes more of a structural question than a fundamental material one at the coupon level. Implicit in many of the papers reviewed here is the assumption that an externally applied compressive load results in a state of uniaxial compressive stress in the gage-section of the composite specimen. Compression failure is then a result of this state of stress. Efforts to achieve a state of uniaxial compressive stress have directed the development of test methods towards designs with the shortest possible gage-length, but not all test methods achieve this objective. This is a worthy goal and the right approach for determining intrinsic material properties, but is this the information that is most useful in the final application of the data? The answer may lie in observing the extreme efforts that are necessary to induce "material compression failure" even in the most controlled environment, the test laboratory. Are these controlled conditions to be expected when a composite component is subjected to its service environment?

These observations tell us that there is no single definition of compression failure strength. The two extremes are global elastic Euler buckling and material compression failure. Between these two extremes lies a transition region in which the state of stress that exists is a combination of bending induced stresses and compressive stresses. To illustrate this issue consider figure 1. This figure shows the the spectrum of response of a fiber-reinforced laminated composite to externally applied compressive loads. The term "structural" is used here in the sense that a laminate is considered as a structural element and not in the sense of an end-use structure. The response of a laminate to an externally applied load is on the "structural" level, the resulting state of stress on an element in the strength-of-materials or laminated plate sense is on the "macrostructural" level, and the response on the fiber-matrix interaction level is called the "microstructural" level.

The results of an experimental program that show the extreme sensitivity of specimen geometry and its influence on the compressive response of 0° graphite/epoxy specimens are shown in figure 2. This data has been generated in an IITRI test fixture

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which has been shown to produce the most consistent and reliable data at one specific gage-length. This figure clearly indicates that what is reported as compressive strength from the IITRI fixture is simply the strength from a narrow region of a curve that is very sensitive to specimen geometry, suggesting there is no intrinsic material compression strength.

The perspective of the current literature with respect to figure 1 is that the theoretical papers in the open literature fall within the microstructural response level, while the papers dealing with test methods and experimental data fall within the microstructural response level and the transition region. That is the theoretical papers assume a state of uniaxial compression, but the experimental studies cover test methods and specimens with widely varying gage-lengths, gage-length support methods, and with differing load-transfer schemes. The goals of research programs warrant the use of many test methods, but the implications of a test fixture and specimen configuration should be considered.

Even though composite material compression tests are difficult to conduct and subject to the may factors discussed above, methods to compare and rank composite materials based on their compression strength are necessary. Using this information to design composite components for compressive loading is not a straightforward task. The above discussion is intended to alert the reader to the issues to be considered when conducting compression tests, reviewing compression related research, or using compression data for component design. As a conclusion, the last section of this paper provides a synopsis of our current compression testing practices and the most recent philosophy of compression failure processes. Guidelines for designing compression tests that require a deviation from accepted practices are suggested.

COMPRESSION TEST METHODS

GENERAL

Many investigators have been interested in the effect of test configuration and specimen configuration on compression response of advanced composites. Because compression test results are sensitive to many experimental parameters, some have attempted to determine the most suitable test method for specific material systems or laminate stacking sequences. Others have investigated specimen design to determine the effect of load introduction and gage length on the state of stress in the test section and the buckling stability of the specimen. This section will discuss papers that have dealt with the above concerns. The discussion is divided into a section on the evaluation of test fixtures and a section on the evaluation of compression specimens. A summary of the papers concerning the evaluation compression test methods is included as Table 1.

Test methods found in the discussion to follow are too numerous to describe here; therefore, Table 2 has been provided for the interested reader. This table is a list of the test methods included in the papers reviewed along with the reference that provides a drawing (or schematic) of the method. Table 2 also groups the test methods by classification. In the most general sense, the test methods can be grouped by gage-length restraint (supported or free) then by means of load introduction (shear-loaded or end-loaded), or by load introduction then by gage-length restraint as done here. Other authors have divided the test methods into more specific groups.

Two recent publications, [1]-[2], have listed and discussed the numerous test methods proposed for compression tests of fiber-reinforced composites. Whitney, Daniel and Pipes [1] include a section on compression testing in their text on experimental mechanics. They classify compression test methods into three types by specimen description; Type I being those with a short and unsupported test section length; Type II being those with a long and fully supported test section length; and Type III are those with straight-sided coupons bonded to a honeycomb core. In Type I they describe the Celanese, Illinois Institute of Technology Research Institute (IITRI), Northrop, and National Bureau of Standards (NBS) [3] methods, in Type II

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the Southwest Research Institute (SWRI) and the Lockheed [4] methods, and in Type III the Edgewise Honeycomb and 4-Point Bend Honeycomb methods.

The discussion by Whitney et al. points out that Type I fixtures all yield acceptable data. However, the Celanese test method requires extreme precision in mounting the specimens in the fixture, the mass of the IITRI test method requires prolonged soak periods for elevated temperature testing, and all Type I fixtures require specimen edges and/or tab surfaces be close to perfect in parallelism.

They report that the Type II test methods yield data compatible with Type I data for laminates, but yield consistently lower strength for unidirectional specimens than

the Type I fixtures. For Type III test methods the authors point out values for v_{xy} are often higher than values from tension tests, and that these methods usually yield higher strength than any of the other test methods.

Abdallah [2] conducted a literature review that also discussed available compression test methods. In addition to the methods discussed in ref. 1, Abdallah reviews the Wright-Patterson, Rockwell, Narmco, Boeing, Texaco Experiment, Inc. (TEI), Royal Aircraft Establishment (RAE), ASTM D695, and Federal Standard Test Method 406. Abdallah classifies compression test methods as Group I, specimens loaded through friction (shear-loaded); Group II, end-loaded specimens; Group III, end-loaded with lateral restraint; and Group IV, other test methods such as sandwich beams, rings, and tubes. He then discusses the specimen and fixture configuration for each test method and summarizes the results of published test method evaluations.

After his review of independent test method evaluations, Abdallah concluded that no method is universally accepted throughout the testing community, but that the two best compression test fixtures are the IITRI and the Sandwich Beam in 4-point bending. Based on the performance of the IITRI fixture Abdallah recommends a new design that is claimed to be an improvement on the current IITRI design. His design is smaller than the current one and incorporates linear bearings between the wedge grips and the grip housing to eliminate friction that may occur there. The new fixture has not been manufactured so fabrication or experimental problems are not resolved. The less massive wedge housing would need to be evaluated for adequate stiffness.

FIXTURE EVALUATION

Adsit [5] reports on the results of an ASTM Committee D-30 (High-Modulus Fibers and Their Composites) round robin test of various compression test methods currently in use. At the time of testing the only compression test method recommended by ASTM for aligned fiber composites was ASTM D3410 [6], the Celanese test method. Results are presented for 4 unidirectional material systems (E-glass/1002, AS/3501, T300/5208, T300/934) tested by nine laboratories. The four test methods evaluated were ASTM D695 [7], ASTM D3410 (Celanese method), IITRI, and the Sandwich Beam 4-point bend test. Material was prepared by one source and distributed to each investigator to tab, cut, instrument and test. Consequently, material inconsistencies were eliminated in this study. However, specimen preparation sensitivity is not.

The results from this investigation indicate that modulus of elasticity is not a function of loading method. Strength data for the end-loaded D695 test method was lower than for the other three test methods and is attributed to premature failure from stress build-up on fibers that are not the same length on the specimen ends. Consequently ASTM D695 is not recommended for advanced composites. The strength results from this investigation were the same for the Celanese, IITRI, and sandwich beam test methods. The paper does point out that the Celanese (conical) fixture can be misused by not controlling the total specimen thickness. Poisson's ratio was not determined during these tests.

The final recommendation from this round robin evaluation is that ASTM D3410 be modified to include the IITRI fixture and the sandwich beam fixture in addition to the already recommended Celanese fixture. This modification is to be included in the forthcoming revision of ASTM D3410.

Clark and Lisagor [8] were interested in evaluating the effect of specimen thickness, laminate orientation, support arrangement, and method of load transfer on graphite/epoxy composites. The three test methods they investigated were a shear-loaded method (IITRI), an end-loaded method (NASA), and a face-supported method. Specimens of 12.5, 25, and 50-mm widths, 8, 16, and 24 ply thickness, and [0], [±45], and [0/±45,90] orientation were evaluated in the IITRI and face-supported fixtures. [0/±45/90], 16 ply specimens were tested in the NASA fixture.

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Clark and Lisagor conducted a thorough experimental investigation and included in their results a discussion of *Uniformity of Load Transfer, Compressive Strength and Stiffness , Comparison of Strength by Fixtures, Specimen Thickness Effects, and Failure Modes*. Their major findings included the results of a study on the sensitivity of IITRI generated stress-strain response to tab flatness. Three plots show stress-strain response for as-fabricated specimens, specimens with tabs ground flat

and parallel within ±100 μm, and specimens with tabs ground flat within ±25 μm. Strain response from 4 gages was acceptable only after the final grinding.

A wide range of strength of [±45] style specimens resulted from compression tests in the IITRI fixture. This is attributed to the effect of the high Poisson's ratio in specimens of the tested widths. The IITRI fixture yielded the highest strength of the three for 16-ply, 25-mm-wide quasi-isotropic specimens. The average value of modulus was approximately the same for all fixtures.

The general conclusion from this paper is that no single test fixture is adequate for the all of the specimens tested, the IITRI fixture provided the most consistent data for unidirectional specimens, and the face-supported fixture produced the most consistent data for the [±45] specimens. Finally, the data produced by the NASA end-loaded fixture was not substantially different from the IITRI and face-supported fixtures, so the simplicity of the NASA specimen and fixture has led to its use at NASA Langley for additional compression testing of composite materials [9].

The development of the IITRI fixture is discussed in a paper by Hofer and Rao [10]. The design was an attempt to eliminate shortcomings in test methods used at the time. The Celanese fixture was the most promising fixture at that time, and the IITRI fixture eliminated the cone-to-cone seating problems often associated with it. As part of their investigation Hofer and Rao compared the compressive moduli of aluminum, brass, and steel to the respective tensile moduli to determine the frictional performance of the system. Their tests results indicated frictionless performance of the IITRI test fixture.

Lamothe and Nunes [11] investigated the effect of test method on the compressive response of laminates of five material systems, each with a different fiber orientation. They tested T300/5208 graphite/epoxy $[0]_{16}$ specimens, S2/SP-250

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glass/epoxy $[0/\pm45/90]_{2s}$ specimens, Kevlar 285 weave/Cycom 4143 Aramid/epoxy specimens, unidirectional FP alumina/aluminum specimens, and unidirectional FP alumina/magnesium specimens in Celanese and IITRI fixtures. For the organic matrix composites they found the IITRI fixture easier to use and more flexible in testing specimens of differing thicknesses. The two test methods yielded the same modulus results and the IITRI yielded somewhat higher strength results although a small specimen population was tested.

Neither the Celanese nor IITRI fixture was suitable for testing the metal matrix composites (MMC's). Tab failures occurred in specimens of suggested design. Thinner specimens were then manufactured to induce compressive failure, but the higher length-to-thickness ratio caused global buckling failure. Reduction of the gage section length to reduce length/thickness made strain measurement difficult, so a new specimen was designed for the MMC's. The specimen was a short, cylindrical end-loaded type with capped ends.

Finally in the area of test fixture evaluation, Irion and Adams [12] designed and evaluated two fixtures for creep testing of composites while Daniel and LaBedz [13] evaluated a new dynamic compression test fixture. The results of these studies are discussed in the EXPERIMENTAL INVESTIGATIONS section.

SPECIMEN EVALUATION

References 14, 15, 16, and 17 are theoretical studies that deal with the effect of tabbing, load introduction, and specimen geometry on the state of stress in the gage section of compression specimens. Reference 18 describes the reusable sandwich beam test method and reference 19 is an experimental study determining the effect of gage length on the compressive response of graphite/epoxy tested in the IITRI fixture.

Bogetti, Gillespie, and Pipes [14] were interested in the effect of specimen design on the compressive response of IITRI specimens. While most investigators design to an upper limit on gage-length to prevent Euler buckling, their study considered both the upper and lower bounds of specimen gage-length. Gage-length must be short enough to preclude buckling failure, but long enough for the state of stress to decay to a state of pure compression in the test section. An elasticity solution

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based on Saint-Venant's principle and a finite element method are used to establish the gage-length lower bound. The gage-length upper bound was determined based on a conservative estimate of critical buckling strain assuming pinned end conditions and including the effects of transverse shear deformation. The analyses allow for variations in specimen geometry (length/thickness) and varying material anisotropy, E_x/G_{xy} (longitudinal stiffness/inplane shear stiffness).

The results from this study demonstrate that ASTM-D3410-recommended specimen geometries for shear-loaded test methods (IITRI and Celanese) are appropriate for Boron/Epoxy, Graphite/Epoxy (E_x/G_{xy}=30.5), and Glass/Epoxy. However, as E_x/G_{xy} ratios increase, the gage length upper limit decreases and the gage length lower limit increases so caution must be exercised when generating compressive test data for highly anisotropic materials. A graph showing allowable length/thickness ratios as a function of E_x/G_{xy} is included and provides a convenient means for selecting specimen geometry for the IITRI and Celanese type test methods.

Reiss, Yao, and Clark [15] used the principle of minimum complementary energy to determine the effect of constraining action by grips on the state-of-stress in the gage-section of compressively loaded composite coupons. Their analysis assumed clamped ends which were allowed to undergo pure compression and pure bending. They present results for the analysis of [0/±45/90]$_s$, [±45]$_s$, and [0] graphite/epoxy laminates. Their results include values of σ_x, σ_y, and τ_{xy} within the gage-section of the specimen and a recommended length-to-width ratio that allows for a state of uniaxial compressive stress at the midlength of the gage-section. A length-to-width ratio of .75 is recommended for the [0/±45/90]$_s$ laminates, 1.5 for the [±45]$_s$ laminates, and it was found that the constrained edge influence is limited to a small region near the corners of the gage-section for the [0] laminates.

Rehfield, Armanios, and Changli [16] were also interested in the design of compression specimens. However, they analyzed end-loaded specimens with tabs. The tabs on these specimens are claimed to eliminate the need for test fixtures such as the IITRI or Celanese, prevent end brooming, and stabilize against buckling. The analysis developed in this program is in closed form and based on the assumption that

classical bending theory can be used to estimate transverse and normal strains. The analysis is used to estimate τ_{xz} and σ_{xz} at the tab specimen interface, axial strain at the tab termination, and strain uniformity in the gage section. The results in the paper are presented for end-loading a standard size IITRI specimen, although a specimen of this geometry is likely to buckle under simple end loading. The results from the closed form solution were compared to a finite element model and the results compared graphically. The results of this paper would be more useful if the analysis had been used to suggest a tabbed, end-loaded specimen design as proposed by the authors, since the standard IITRI specimen will not perform satisfactorily under these loading conditions. No specimen design is suggested.

Woolstencroft, Curtis, and Haresceugh [17] used a 3-D finite element analysis to determine σ_x, σ_y, and σ_z for the shear-loaded Celanese, end-loaded RAE, and end-loaded ASTM D695 specimens. All three specimen types yielded negligible σ_z stresses. Both the ASTM D695 and Celanese experienced transverse compressive stress, with only the RAE specimen having uniform σ_x and negligible σ_y.

The Sandwich Beam in four-point bending has been a very popular compression test method for advanced composites. One concern with this method is the effect the honeycomb core has on the state of stress in the composite facing. Shuart [18] theoretically determined the biaxial state of stress in the composite skin and the percentage of load carried by the core. A 3-D linear finite element analysis was used. The analysis indicated the transverse stress in the composite face was negligible for the honeycomb core (aluminum or titanium) and graphite/polyimide materials if ribbon direction modulus of the honeycomb is no greater than 1765 kPa. The analysis also showed that less than 1% of the load is carried by the honeycomb core, even for 90° specimens.

Although compression test results generated by the Sandwich Beam method are highly acceptable, the main disadvantage of the method is the large amount of material required for the specimen and the cost of the sandwich beam that can only be used for one test. This weak point motivated Gruber, Overbeeke, and Chou [19] to design and

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evaluate a "reusable sandwich beam" compression test method. Their design uses a 254-mm long by 12.7-mm wide specimen with tabs on one surface that is clamped to a sandwich beam constructed of aluminum honeycomb, a graphite/epoxy tension face, and a plexiglass core under the specimen gage-section. A Kevlar/glass phenolic hybrid composite system was evaluated in the reusable sandwich beam and the results were consistent with tests run in an IITRI fixture.

Smoot [20] tested AS1/3501-6 graphite/epoxy in the IITRI fixture using specimens of standard width (6.4-mm) and standard tab length while varying the gage length-to-thickness ratio from (4.4 to 47.1). Sixteen length/thickness ratios were tested, four specimens at each ratio. The major result of this investigation is evident from a plot of ultimate compression strength versus length/thickness ratio, figure 2. For length/thickness ratios greater than 8.7 the strength drops rapidly with small increases in length/thickness. There was also a decrease in strength for decreasing length/thickness ratios between 8.7 and 4.4 , but the decrease was not as rapid. Since the compressive strength does not approach an upper bound and remain constant, this data points out the sensitivity of compression response to specimen geometry and suggests that there may not be an ultimate compressive strength for unidirectional composites. If ultimate compression strength is defined as the highest compressive strength that can be measured in a given test fixture, then the range of gage lengths for specimens tested in the IITRI fixture is very limited.

Smoot also reports changes in the failure modes and end condition factor (pinned versus clamped) for increasing length/thickness ratios. Calculated from the Euler buckling equation, the end condition factor changes from clamped for large length/thickness ratios to pinned for small length/thickness ratios.

DELAMINATION AND DAMAGE TOLERANCE

An area in which compression testing has played an important role recently is in determining the delamination resistance and damage tolerance of composite materials. It has been recognized that the presence of delaminations and impact damage have a greater effect on the compressive response than the tensile response of composite laminates. Consequently, compression tests are conducted to quantify these effects. The substantial amount of work that has been done in this area warrants a critical

review of its own, so this topic will not be addressed here. However, the information discussed in this paper can and should be applied to research programs in the area of delamination growth and damage tolerance. In the case of delamination growth papers such as those by Gillespie and Pipes [21], Rothschilds, Gillespie, and Carlsson [22] and Whitcomb [23], the delamination growth experiments and models they report on concentrate on a Euler buckling mode of failure that investigators aim to avoid in efforts to determine basic compression strength and stiffness. While providing a clearer understanding of the delamination growth process and the influence of constituent properties and laminate toughness, this failure mechanism surfaces more in the area of structural compression response than in coupon response.

Compression after impact studies such as those presented by Williams and Rhodes [24] and Manders and Harris [25] are certainly influenced by material inhomogeneities, test methods, and constituent properties as discussed in this paper. However a review of work in this area would concentrate on compressive strength after impact, projectile mass and velocity, and area of damage and open up a whole new set of discussions not included in the current paper.

The omission of papers covering work in the area of delamination growth and damage tolerance will not affect the review of papers that concentrate on understanding compression response in its simplest form as intended here.

FAILURE THEORIES AND FAILURE MECHANISMS

GENERAL

Failure theories to predict the compressive strength of fiber-reinforced composites began to appear in the literature in the early to mid sixties. Since the emphasis of this paper is on recent literature, a comprehensive review of the literature from that time to the present will not be included. However, the relevance and motivation for current theories cannot be understood independent of past developments, so as an introduction, a summary of early papers that have had a significant impact on our understanding of compression response will follow.

Although many failure modes have been observed and suggested to explain compression failure, the analytical models that have been the foundation of our current understanding include fiber buckling models, transverse tension models, and fiber kinking models.

Fiber Buckling

A large percentage of the proposed theories are based on the stability of fibers in a flexible matrix. One of the earliest and the most referenced publication on stability-related compression failure is the paper by Rosen [26]. In this paper Rosen presents a two-dimensional model of columns supported by an elastic foundation as the basis for compression failure of unidirectional composites. Basing his solution on energy principles, Rosen proposed that failure constituted the short-wavelength buckling of the fibers in two modes, an extensional mode and a shear mode. In the extensional mode the fibers buckle out of phase, and in the shear mode the fibers buckle in phase as shown in figure 3. Two expressions for the ultimate compressive strength result, and the lower value is used for the strength. The equation for the shear failure mode results in the lower strength for most composite materials.

The strength predictions provided by Rosen's analysis yield theoretical strengths that have been shown to be higher than observed experimental results for fiber-reinforced composites. Experimental efforts to investigate the microbuckling

theory followed and the most comprehensive study was conducted by Greszczuk [27-31]. Greszczuk manufactured highly controlled composite specimens of laminae (plate)-reinforced, circular-fiber (rod)-reinforced, and actual graphite fiber reinforced composites. The study investigated the effects of different constituent properties, fiber array, bowed, unbonded, and misaligned fibers. Greszczuk concluded microbuckling models can predict the compression failure of ideal laminae-reinforced composites, but not the failure of circular-fiber composites or actual composites. He concluded further that laminae-reinforced composites consisting of a low-modulus resin fail by microbuckling, but as resin modulus increases the failure mode changes and failure is governed by the compressive strength of the reinforcement. Refinements of the fiber buckling theory have been proposed that include nonlinear effects [32], fiber curvature [32, 33], and partial bonding [27, 34]. A historical review of the proposed compression failure theories that deal with the short-wavelength buckling phenomenon can be found in a publication by Shuart [35].

Transverse Tension

Another phenomenon considered to explain the discrepancy between theoretical and experimental compression failure results is the presence of transverse tensile stress in unidirectional composites subjected to compression loading. Even though the resulting transverse tensile stress is small, it can be significant enough to cause failure in unidirectional composites due to their low transverse strength. Greszczuk [27] used an interactive failure theory relating transverse tensile failure to uniaxial compressive stress to predict ultimate compression strength.

Fiber Kinking

Kink band formation in composites subjected to compressive loads is also a failure mechanism that has been proposed as contributing to the low compressive strength of composites. Hahn et al. [36] point out that anisotropic materials are susceptible to kink banding and reference the appearance of kink bands in oriented rods of polyethelyne, oriented rods of nylon, anisotropic rocks, paperboard, and wood. Since elastic buckling analyses alone are not adequate for predicting the

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strength of fiber reinforced composites, and the experimentally observed formation of kink bands in composites subjected to compression involves plastic deformation of the resin, kink band theories have become popular for strength predictions.

Argon [37] suggests that the regions in a composite in which fibers are not aligned with the compression axis will form a failure nucleus that undergoes kinking and occurs at a stress lower than the ideal buckling strength derived by Rosen. Berg and Salama [38] observed kinking in graphite/epoxy composites subjected to fatigue loading.

Weaver and Williams [39] proposed a kinking model that involves buckling of fibers on an elastic foundation, fracture of the fibers at a critical strain, movement of the kink across the width of the specimen, and finally the rotation of the kink towards the axis of principal stress.

Evans and Alder [40] conducted a thermodynamic analysis of kinking in composites in which minimization of plastic work determines kink inclination and minimization of elastic strain energy determines kink boundary orientation. General kink band geometry is shown in figure 3.

RECENT THEORIES AND OBSERVATIONS

In a series of papers, Hahn, Williams, Sohi, and Moon [36, 41, 42] have attempted to explain the failure processes in unidirectional and quasi-isotropic compressively loaded composite laminates. The main thrust of their research was to design and carefully conduct compression experiments that would explain the characteristics of compression failure as a function of the constituent properties in reinforced composites. Their experimental observations led them to propose a non-linear microbuckling theory [41] and an analysis that predicts kink band geometry and compression failure based on kink band formation [36].

In reference 36 Hahn, Sohi, and Williams evaluated the compressive response of fiber bundles embedded in two epoxy resin systems. The fiber bundles tested were E-glass, T300 graphite, T700 graphite, P75 graphite, Kevlar 49, and FP alumina. They observed that bundle failure characteristics were the same as those reported for the same single fibers embedded in a matrix. The highly anisotropic Kevlar and P75 fibers failed by kinking of microfibrils, and the E-glass, T300, T700 and FP alumina

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fibers failed by microbuckling. They also found that fiber buckling was uniformly distributed in specimens with the lower resin modulus (2.13 GPa), and quite localized in the specimens with higher resin modulus (3.45 GPa).

Unidirectional composite laminates were tested in compression by Hahn et al. in reference [36] and [41]. These laminates had the following constituents: T300 graphite fibers in epoxy resins of varying modulus, PPS and PEEK, T700 graphite fibers in epoxy resins of varying modulus, and S2-glass and Kevlar 49 fibers were tested in one epoxy.

From the results of their experiments on fiber bundles and unidirectional composites, Hahn and coworkers concluded the following about compression failure in unidirectional composites. If the fibers are weak in compression, they fail in compression before buckling and cause laminate failure. If the fibers are not weak in compression, failure initiates as microbuckling from the instability of fibers that have the least lateral support due to free-boundaries, the formation of longitudinal splitting, the presence of voids, or at stress concentrations due to test hardware If the matrix is soft, the fibers will fail in bending due to continued microbuckling. If the resin is stiff, failure takes the form of kinking. Regardless of the mode of incipient failure, Hahn et al. further conclude that all compression failures of composite materials of the class that they studied exhibit final failure in the form of kink bands. That is, although microbuckling or compression overstressing may initiate failure, each lead to the formation of kink bands in final failure when the resin system is of adequate stiffness. They also state that microbuckling is the cause of kinking in most composite systems.

Sohi, Hahn, and Williams [42] also investigated the response of 24-ply $[45/0/-45/90]_{3s}$ quasi-isotropic laminates reinforced with T300 and T700 graphite fibers. The resins in this study were the same four epoxy systems used in the unidirectional laminates evaluated in reference 36 and 41. This choice of constituent properties allowed a comparison of failure sequences for laminates with matrices ranging in toughness from 5208 (failure strain 1.4%) to BP907 (failure strain 4.8%). Compression tests were conducted in an IITRI test fixture. Failure was catastrophic for all of the laminates although in some specimens failure was arrested by loading to a certain level and then unloading. For the partially failed specimens, failure was observed to be initiating as kinking of the 0° ply. Failure then proceeded as

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delamination and sublaminate buckling. The effect of resin toughness on the failure progression was that failure was quite sudden and arrest of fiber kinking was difficult for the T300/5208 (brittle) laminates, while when the T300/BP907 laminate was loaded to 81% of the ultimate compressive strength, failure was limited to kinking of the 0° and no delamination was present. Although the tougher resin resists the propagation of delamination, the BP907 resin allowed fiber kinking at lower strains than the other resins. This observation again points out the dependence of microbuckling initiation on resin modulus, and signals the need for awareness that the lower modulus usually associated with tougher resins means a trade-off between delamination resistance and microbuckling initiation. Compressive strength increased with tensile modulus for the quasi-isotropic laminates and their failure strains were higher than for the unidirectional laminates.

Sohi et al. also investigated quasi-isotropic laminates with holes in their study and found failure initiation to be fiber kinking in 0° plies. As in the case of the unnotched laminates the failure progression following fiber kinking was dependent upon the resin toughness.

Budiansky [43] presented a review and discussion on the application of kink band theories to the compression failure of composites. He proposes a solution for the maximum composite compression strength based on plastic kink band formation. He concludes that the factors affecting kink strength of composites are understood, that high shear stiffness and strength are desirable, and the sensitivity to fiber misalignment is high. Budiansky also proposes solutions for kink band angle and width, but adds while our understanding of kink band geometry is qualitatively sound, quantitatively we need to include the influence of random imperfections in our analyses.

While most analyses to determine the compression response of composites are for unidirectional systems, Shuart [35] developed an analysis for symmetric off-axis and angle-ply laminates. He uses a linear analysis to determine laminate stress and strain and short-wavelength (microbuckling) mode shape. A nonlinear analysis including the effects of initial imperfections (fiber-waviness) is used to determine inplane and interlaminar shear strains. Both analyses are based on the principle of minimum potential energy and are 2-D models of plates on elastic foundations. Results presented include the short-wavelength mode shapes for off-axis and angle-ply laminates from the linear analysis. Laminate stresses, out of plane displacements, and

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interlaminar shear strains are generated by the nonlinear analysis and reported for [0], [0/90], [±45] and [+45/0/-45/90] graphite/epoxy laminates. Significant interlaminar shearing strains occur at stresses lower than those causing short-wavelength buckling and compression failure criteria is described that includes inplane shear, interlaminar shear, and short-wavelength buckling failure mechanisms.

Piggott and Harris [44] conducted an experimental study to determine the effect of resin properties on compression strength of composites. Short pultruded solid cylinders were tested with high-strength graphite fibers, high-modulus graphite fibers, E-glass fibers and Kevlar 49 fibers. The cylinders were manufactured such that the polyester resin was in various stages of cure resulting in varying degrees of modulus and strength. The fiber volume fraction of the composites in this study was 30%. The graphical results included in this paper are for the E-glass composites and show the compressive strength is a strong increasing function of matrix yield strength up to 60 MPa. Results also show that the composite modulus follows a rule of mixtures relationship up to a fiber volume fraction of 45% and the composite strength follows a rule of mixtures relationship up to 30% fiber volume fraction.

Piggott and Wilde [45] then conducted a study to determine the effect of fiber strength on the compressive strength of aligned fiber-reinforced epoxy. The composites were reinforced with steel rods hardened to different degrees to control their strength. From their results, they developed a rule of mixtures relation for ultimate compressive strength in terms of fiber and matrix volume fractions, matrix compressive strength, and the flexural strength of steel. The theoretical and experimental results were in good agreement for the steel/epoxy (V_f=15%, 34%) composites evaluated.

As a result of the experimental results Piggott developed, he found the need to formulate a new theory for compressive strength. He recognized the different failure mechanisms that contribute to failure, and developed his theory accordingly in reference 46. Six governing equations are proposed with each accounting for a different failure mechanism, and the one that yields the lowest strength is considered the active one. All of the models are rule-of-mixtures type that represent ultimate strength (or modulus) as a function of fiber and matrix strengths, stiffnesses and volume fractions. The first model assumes compression failure of the fibers, is used

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for composites reinforced with ductile fibers, and is the rule-of-mixtures formula discussed in reference 45. Four more failure models are proposed that stem from the presence of fiber waviness. The first determines the reduction of composite modulus as a function of fiber curvature. Three others predict composite strength based on the response of the matrix and fiber-matrix interface due to increasing fiber bending under the influence of compressive loads. These models are for matrix yielding (matrices with low yield strength), transverse splitting (low adhesive strength), and transverse compression. The sixth model accounts for fiber-to-fiber interactions present in hybridized composites.

Piggott compares his models with experimental data for glass/polyester and Kevlar/polyester and finds good agreement. This work is an interesting effort to explain the compressive response of composites with models that are simple yet account for a number of different failure mechanisms.

Sinclair and Chamis [47] proposed a series of failure theories in a manner similar to Piggott. Their theory included four governing equations to account for different failure mechanisms. The objective of their work was to describe the compressive strength of a composite from its tensile and flexural strengths. The first mechanism modeled was global Euler buckling using the classical fixed-end column equation not including the effects of transverse shear. Next they determined the compressive strength from the flexural strength assuming a rectangular stress distribution in beam in three-point bending. The third model predicts delamination-controlled compressive strength from apparent interlaminar shear strength and is an empirical curve fit from NASA Lewis data. The final model assumed fiber compressive strength failure and is a rule-of-mixtures type micromechanics model. Sinclair and Chamis conduced IITRI compression tests on unidirectional AS/PR288 and T300/5208 graphite/epoxy laminates for comparison with their failure theories. The results for the AS/PR288 laminates indicate that the strength is predicted by the interlaminar shear model therefore strength is controlled by delamination. The compressive strength of the T300/5208 laminates fall into three groups, a high, medium and low-strength group. The failure of the high-strength group was predicted by fiber compressive failure, the medium strength group by flexure or delamination, and the low strength group by Euler buckling (unsupported gage length assumed to extend into tabbed region).

Batdorf and Ko [48] developed an expression to determine the failure of unidirectional composites under combined compression and shear. Their analysis is based on fiber kinking and subsequent plastic yielding of the matrix as in the work by Budiansky [43] and Hahn et al.[36]. This analysis differs in that it includes the effect of combined loads. When shear stress is neglected this solution reduces to Budiansky's solution exactly (assuming elastic-perfectly plastic matrix response), and to Hahn's solution (assuming matrix strain-hardening) within a factor of fiber volume fraction. Limited experimental comparison shows the theory may work well for materials that can survive large shear strains.

Chou and Kelly [49] indicate the importance of including transverse shear effects when analyzing the compression response of composite laminates. The effect of transverse shear in a composite must be considered because of the high longitudinal-stiffness-to-shear-stiffness ratio. Including transverse shear reduces the load or strain required to cause global Euler buckling and can be significant for unidirectional composites.

Oriented polymer composites are not conventional fiber-reinforced composite materials, however they exhibit similar mechanical characteristics because of their anisotropy. For this reason DeTeresa, Porter, and Farris [50] choose to apply the classical elastic stability analysis discussed in the fiber buckling section to the buckling of extended chain polymers. Their model predicts the compressive loads required for buckling of a long single polymer chain. In this analysis the polymer chain was modeled as series of rigid links of equal length connected by elastic hinges of equal stiffness. Using a differential equation for the static equilibrium of the chain, DeTeresa showed that the curvature of the buckled chain is proportional to the angular change between hinges (or bond angle deformations). The final result is that the differential equation describing the buckling of the link-hinge chain and a continuous column are completely analogous. In addition the bending stiffness of the link-hinge chain is the product of the link length and the hinge stiffness and can be substituted into the classical buckling load equation for EI, the bending stiffness of a continuous column. An oriented polymer fiber is then analyzed by considering single chains that interact through lateral bonding. As in the case of fiber-reinforced composites, compressive strength of an oriented polymer based on the microbuckling of the chains is higher than experimentally observed strengths. Suggested explanations for the

discrepancy include buckling of chains at the surface of the fiber at one-half of the predicted load, the presence of voids, areas of lateral interaction where elastic support is lower than modeled, presence of residual stresses, and the misalignment of chains. DeTeresa also points out that the presence of these local inhomogeneities are sites for the initiation of kink bands.

In a short paper on the compressive response of aramid reinforced composites, Van Dreumel [51] suggests that the use of aramid composites for compressive loading should not be ruled out just because they have low compressive strength. He points out that in a structural buckling analysis, the Euler buckling strength of a graphite composite is only 1.3 times that of an aramid composite. Since aramid has a lower density than graphite, he states that an aramid panel will be thicker providing greater handleability and greater impact resistance.

The work by Kim [52] compared the tensile and compressive response of off-axis and angle-ply laminates to results predicted by the Tsai-Wu tensor polynomial failure theory. The experimental compression results compared favorably with the failure theory when the value of the interaction term (F_{12}) was based on the Von Mises yield criteria for isotropic materials $(F_{12}=-0.5)$. This paper is the only one reviewed that discusses compression failure on the macrostructural level. A review of the literature on macromechanical failure theories may provide compression failure data, but the current search of compression related literature did not reveal any work other than that of Kim. A comprehensive review of macromechanical failure theories is presented by Nahas [53], and this work would be an excellent source of information for analyzing compression failure on a macromechanical level using interactive failure theories. Nahas does not refer to any work that evaluates the applicability of proposed failure theories to compression response specifically.

The last five papers to be discussed in this section deal with experimental investigations in which the authors made careful observations of the failure characteristics of composite laminates loaded compressively. In all of these papers the laminates tested contained holes.

Potter and Purslow published two papers [54 & 55] dealing with the response of graphite/epoxy laminates subjected to exposure to moisture and temperature. Their laminates were 30-mm wide by 160-mm long, 24-ply Fibredux 914/XAS panels with

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50% 0° plies, 50% ±45° plies, and 4.83-mm holes. The specimens were supported around the perimeter of the test section with a 20-mm wide by 44-mm long unsupported test section. The first paper reported the results for tests run under room temperature dry (RT-D) and hot-wet (H-W) conditions. Some specimens tested in the hot-wet conditions were preloaded to 66.7% of their hot-wet ultimate strength to determine the effect of preload on subsequent compression response. The second paper reported results from tests on specimens tested room temperature wet (RT-W) and high temperature dry (H-D) to compliment the results from the first program. One unique aspect of the program by Potter and Purslow was their attempt to arrest the compression failure process in its early stages for inspection purposes. This was accomplished by monitoring changes in strain in the vicinity of the hole using metal foil strain gages. Their observation was that at specimen failure strain close to the hole suddenly changes about 20-50 ms prior to final failure. By monitoring changes in strain response, initiation of final failure was detected and the test machine actuator was reset by a subroutine in the program used to generate the displacement control ramp.

Both papers by Potter and Purslow contain very complete discussions of the failure characteristics including SEM and low magnification photographs. Their conclusions state that under RT-D, RT-W, and H-D there is little or no notch sensitivity in compression. The ply cracking and delamination around the hole serve to relieve the stress-concentration caused by it. In the H-W condition, notched-strength was lower than unnotched-strength and the absence of axial splitting suggested no stress relief occurred around the hole. From the specimens subjected to a preload prior to compression testing, it was concluded that the level of preload applied had no effect on the environmental test that followed.

Shuart and Williams [56] investigated the compressive response of ±45-dominated laminates with holes and impact damage. Six ±45°-dominated laminates were evaluated with various percentages (0-33%) of 90° plies. All specimens were 127-mm wide and 254-mm long, and tested either unflawed, with holes (6.4-50.8-mm dia.), or after impact loading. The primary compression failure mechanism for the all ±45° laminates with holes was in-plane matrix-shearing. For ±45°-90° style laminates with a hole, failure mechanisms were a combination of matrix-shearing and delamination. The percentage of delamination failure increased

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with increasing percentage of 90° plies. Matrix-shearing is defined as in-plane shear failure and originated at the hole boundaries and extended outward parallel to the fiber directions. The failure mechanisms for the impact damaged specimens was predominantly delamination, but matrix shearing was observed.

Glass/epoxy all ±45 birefringent specimens with holes were also tested, then illuminated with polarized light to observe stress concentration patterns. Regions of maximum stress were indicated at the hole boundary on the horizontal axis of the specimen that correspond to the areas where failure initiated. Visual inspection revealed that fiber kinking along the boundaries of the matrix-shear bands.

Knauss and Henneke [57] studied the compressive failure of graphite/epoxy plates with holes. Unflawed plates and plates with holes from 1.6-mm to 38-mm in increments of 3-mm were tested to failure in compression. 24-ply and 48-ply (±45/90/0) style laminates were tested in both quasi-isotropic ($E_x/E_y=1.0$) and orthotropic ($E_x/E_y=2.015$) configurations. The panels in this investigation were large, 127-mm wide x 254-mm long, so buckling failure modes were experienced for the panels with lower stiffness (transverse direction for the 48-ply orthotropic panel) and the panels with high l/t ratios (both 24-ply laminates). The sequence of events leading to failure for the 48-ply orthotropic plates consisted of local delamination, local buckling, and panel collapse. A threshold existed between $0.504 \leq$ Dia. /Thickness ≤ 1.01 at which failure changed from buckling to compression. The 48-ply quasi-isotropic laminates failed suddenly and catastrophically. Buckling failure dominated for all of the 24-ply laminates with hole dimension having little effect on buckling load. From the experience the authors gained in testing the 48-ply laminates, the dimensions of the 24-ply quasi-isotropic laminate were changed so that the failure mode would be strength-dominated. When tested, panel failure was typical of that observed in the 48-ply quasi-isotropic panels.

EXPERIMENTAL INVESTIGATIONS

Papers discussed in this section are concerned with experimental investigations in which the principal objective was to investigate the compressive response of a specific composite material system. A summary of the papers reviewed in this section is contained in Tables 3 & 4. Table 3 also contains a summary of all papers reviewed in this literature survey that contain experimental results.

STATIC COMPRESSION

The investigations by Guess et al. [58] and Leach et al. [59] deal with the through-thickness properties of Kevlar and graphite reinforced epoxy systems. Guess' program was designed to generate data to be used in the design of thick-walled spherical internal pressure vessels in which a composite laminate will be in compression in the radial direction. The laminates in this investigation were cured such that void content varied from 1 to 20 percent by volume. Guess' 25.4-mm long by 11.4-mm dia. cylinders were cut from a thick quasi-isotropic Kevlar fabric laminates. Neat 5209 resin, Kevlar 49 (181 fabric)/5208, Kevlar 49 (181 fabric)/5209, Kevlar 49 (328 fabric)/5208, and Kevlar 49 (3281 fabric)/5209 systems were tested.

Guess found increasing porosity in Kevlar reinforced laminates caused increased yielding at moderate stress levels, a decrease in initial modulus, a reduction in axial compressive strength, and an increase in axial failure strain. Guess also found that most specimens failed along inclined planes breaking through layers of fabric.

Leach et al. reported on the through-thickness response of S2-glass, Kevlar 49 and T300 epoxy composites. The matrix was a Brunswick Corp. LRF (Lincoln Resin Formulation)-215 epoxy. Specimens were cut from filament wound unidirectional and crossply tubes with a 145-mm inner diameter and 25.4-mm wall thickness. The simple curvature on the upper and lower surfaces was left intact on the compression specimens and compensated for with matching machined loading blocks. End load was applied directly to the specimens with no end caps to prevent brooming. Transverse modulus and strength are reported along with plots of the resulting stress

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strain curves.

Ditcher and Webber [60] examined the effects of specimen thickness, orientation, and edge effects on the compressive response of cross-ply carbon epoxy laminates. Their study included $[0/90]_s$ and $[90/0]_s$ laminates of two thicknesses. Experimental compressive response was compared to theoretical predictions from a linear and non-linear analysis. Experimental longitudinal stress-strain response and ultimate compressive strength results were found to compare favorably to non-linear laminated plate analysis and a linear analysis that included edge effects. Transverse strain was significantly affected by the interlaminar free-edge effects in the 2-mm $[0/90]_s$ specimens and varied substantially from the non-linear laminated plate theory, which did not include free-edge effects. The free-edge analysis does account for an increase in transverse strain within a laminate thickness of the edge, and free edge effects would influence 80% of the 2-mm thick 5-mm wide specimens. The transverse strains for the $[90/0]_s$ laminates show only a small increases due to free-edge effects.

Hayashi [61] was interested in the effect of compressive stress on the shear response of epoxy resin since the compressive response of laminated composites is dependent upon the shear modulus of the matrix. To determine the effect, he designed a 60-mm long specimen with a sections of square and cylindrical cross section. Using this specimen Hayashi was able to measure shear modulus as a function of applied compressive stress. Epikote 828 epoxy was evaluated in this study and the results indicate shear modulus decreases with increasing compressive stress. For compressive stress just beyond the proportional limit, a 24% reduction is reported.

Little work has been conducted to determine the compressive creep response of fiber-reinforced composites, so Irion and Adams [12] studied this problem. Two fixtures were designed for creep testing based on the advantages and disadvantages of current static compression test fixtures. The first is a Celanese/IITRI type shear loading fixture that is claimed to be less bulky than the IITRI while more stable than the Celanese fixture. The other fixture is an end-loaded design with four steel blocks to clamp and support the specimen ends, and bearing supported guide rods for alignment of the steel blocks. Longitudinal and transverse data is reported for graphite/epoxy and glass/epoxy systems. Results indicate that longitudinal graphite and glass reinforced composites creep little, if at all . Transverse specimens exhibited

higher strains than longitudinal ones with long periods of no creep followed by abrupt jumps. Expanded strain versus time plots were recorded in this study and the irregularities in the curves suggest local failures occur almost continually, but are quickly arrested. The tests in this study were run for less than 200 hours and most specimens tested did not attain a steady state creep rate. Both of the fixtures designed for this program worked satisfactorily for creep testing.

The investigation by Kar, Herfert, and Kessler [62] microscopically compared the failure surfaces of AS1/3501-6 specimens tested under room temperature dry and elevated temperature wet conditions. The relation of this work to that of others is difficult since no specimen geometry or test fixture description is included in the paper.

Walrath and Adams [63] developed test methods for determining the mechanical properties of 3-D carbon-carbon composite materials. Their study evaluated methods to determine the tensile, compressive, and shear properties of 3-D carbon-carbon. For compressive properties they evaluated a reduced-section short-length block specimen and found it adequate for determining properties in all three coordinate directions.

DYNAMIC COMPRESSION

The previous discussions on compression test methods and failure characteristics in this paper are for the static response of composite materials, and the majority of the research on compressive response has been for static loading. The number of proposed test methods and the complexity of the failure process for static testing hints at the difficulties in trying to understand the dynamic compressive response of fiber-reinforced composite materials. For instance in the fatigue work to be discussed below no two investigations were performed with test specimens of the same geometry or in the same fixtures. A complete discussion of the recent papers on compression fatigue will not be included here, but the papers will be briefly reviewed and summarized in Table 4.

Saff, Badaliance, Baldini, and Dill [64, 65, & 66] conducted a study on the fatigue response of bolted joints. Five bolted joint specimens were designed to represent the areas containing critical joint designs on the wing structure of the F-18 and AV-8B aircraft. Reference 64 is a literature review on fatigue life prediction that was the first stage of the program. References 65 and 66 present the comprehensive

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test data results and the proposed fatigue life prediction for the composite structures of interest.

Highsmith, Stinchcomb, and Reifsnider [67] present an overview of the damage development processes in composite laminates subjected to fatigue loading. The paper deals mainly with tension-tension fatigue since the knowledge base is most developed for that regime, however tension-compression and compression-compression fatigue response is discussed in light of tension-tension response and limited experimental work.

The experimental configuration for compression fatigue studies is very inconsistent as seen in the summary of the studies discussed here (Table 4). Many investigators use the aid of anti-buckling guides to prevent global Euler buckling of specimens with high length to thickness ratios. Matondang and Schütz [68] studied the effect of anti-buckling guides on compression fatigue results. The effect of t n guides were evaluated on $[\pm45]_{8s}$ and $[0_2/\pm45/ 0_2/\pm45/90]_s$ graphite/epoxy specimens.

The effect of delamination growth in graphite/epoxy laminates was investigated by Ramkumar [69] and Mohlin et al. [70]. Ramkumar nondestructively tracked the growth of imbedded Teflon circular and through-width delamination in 64-ply T300/5208 laminates. Mohlin et al. nondestructively monitored the growth of delaminations around holes in graphite/epoxy composites. Mohlin et al. complimented their experimental program with an analysis of delamination growth using a strain-energy release rate based finite element program.

Grimes [71] and Grimes and Dusablon [72] report a very comprehensive study on the compression response of graphite/epoxy composites. They develop a shear-loaded laterally restrained fixture called the Atmur fixture. Reference 71 includes static and compression-compression fatigue results for 0°, 90°, $[\pm45]$, and $[(\pm45)_5/0_{16}/90_4]_c$ laminates tested room temperature dry, room temperature wet, hot dry, and hot wet. Their second study [72] reports RTD, RTE, HD, HW, and cold wet compression-compression fatigue data for the $[(\pm45)_5/0_{16}/90_4]_c$ laminates with ply drop-offs.

Walsh and Pipes [73] studied the influence of compression-compression fatigue on graphite/epoxy laminates with holes. T300/5208 and T300/5209 materials systems

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were evaluated in $[0_2/\pm45]_{5s}$, $[0/45/0/-45]_{5s}$, $[0/\pm45/90]_{5s}$, and $[90/0/\pm45]_{5s}$ stacking sequences. They modified the IITRI test fixture to accept 25.4-mm wide specimens for their investigation.

Han [74] evaluated fiberglass/polyester in a random-mat/unidirectional combination at room temperatures and cryogenic temperatures. He studied the cryogenic response of fiberglass/polyester for the application of composites as the supporting structure for a superconductive energy storage magnet.

Daniel and LaBedz [13] report results on the only study in which the compressive response of composites at high strain rates (20-500 sec.$^{-1}$) was investigated. They conduct tests on rings 101.6-mm in dia., 25.4-mm wide, and 6 to 8 plies thick, subjected to a load developed by and explosive charge and transferred to the specimen through water.

SUMMARY AND CONCLUSIONS

COMPRESSION TEST METHODS

Compression testing of composite materials is a process that is inconsistent from program to program and investigator to investigator. However, recommendations and guidelines can be deduced from a review of the published work in the area. Although no single test method will adequately satisfy the many objectives of compression testing programs, some programs will benefit from the selection of tried and tested methods.

For testing unidirectional coupons, shear-loading (Celanese, IITRI, Sandwich Beam) methods are by far the most popular and critically evaluated. The choice of one of these methods when specimen size and environmental conditions allow will help assure avoiding problems that have been experienced in the past, and will result in data that can be compared to those of other programs. The choice of another of the twelve test methods in Table 2 may produce favorable results, but the use of these will be guided by less technology-wide experience.

To summarize the three shear-loaded test methods discussed in this paper, the IITRI and Celanese methods are fundamentally the same test methods, with the IITRI being the more popular and an improved version of the Celanese. Both methods require the investment in the test fixture, tab surfaces that are flat and parallel to a high tolerance, and specimen thickness variations in the Celanese can cause line versus surface loading on the conical wedges. The IITRI fixture is inconvenient for environmental testing because the mass of the fixture makes long soak times necessary. Both of these methods also require a specimen gage-length long enough to allow the transition of the stress state from shear to compression, and all methods require a gage-length short enough to preclude global Euler buckling (including the effects of transverse shear). The Sandwich Beam method requires an expensive specimen and does not yield acceptable values of Poisson's ratio.

The remaining twelve test methods listed in Table 2 are end-loaded type methods. Although simple in concept, they require an awareness that specimen ends must be flat and perpendicular to the load axis, and provisions to prevent end-brooming must be made.

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When planning a compression testing program, specimen design is the next most important consideration. The recommended specimen dimensions for the fixtures discussed above are usually for unidirectional specimens and may need adjustments for testing other than 0° coupons. The effect of specimen width becomes important when laminate testing is performed. The high Poisson's ratio of ±45° type specimens has been shown to influence the state of stress in the gage-section when specimen widths recommended for 0° specimens are chosen. Free-edge effects must also be considered for laminates since recommended specimen width is 6.4 to 12.7-mm for 0° specimens.

Finally, consider program objectives that require the design of unique fixtures or specimens due to limitations in existing designs. For example, in considering a compression test program for thick-section laminates, it may not be possible to utilize shear-loaded test methods since a specimen of this type becomes limited by the tab-specimen shear strength. No matter what the requirements of a test program require, adhering to a few guidelines will help assure accurate and reliable results. For shear-loaded compression test methods, consider;

-the flatness and parallelism of tabs

-the upper and lower limits on gage-length

-Poisson and free-edge effects in laminates

-no stress concentrations or bending induced by the fixture.

For end-loaded compression test methods, consider;

-the flatness and perpendicularity of specimen ends

-provisions to prevent end-brooming

-the upper limit on gage-length

-Poisson and free-edge effects in laminates

-no stress concentrations or bending induced by the fixture.

FAILURE THEORIES AND FAILURE MECHANISMS

Efforts to develop a theoretical understanding of the compressive response of composite materials have primarily been in the area of microstructural response. A summary of the proposed microstructural response of composite materials is shown in figure 4. This figure indicates the influence of constituent properties and local

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inhomogeneities on compression response, and shows a number of proposed failure modes. The shaded boxes show the failure sequence that has been suggested for unidirectional graphite and glass fiber-reinforced composites. The failure sequence can be summarized as follows: for composites with strong fibers and high fiber volume fractions (> 30%), microbuckling in a shear mode (in-phase buckling) will occur, initiated by regions of local inhomogeneities (voids, stress concentrations, areas of weak matrix, free boundaries), and lead to final failure in the form of fiber kinking or fiber overstressing in bending.

The analysis of compression failure as shown in figure 4 is based on the assumption that externally applied loads result in a state of uniaxial compression on the macro scale, yet allows for local inhomogeneities. However, as discussed in the introduction, a state of uniaxial compression stress may not be encountered as a result of an externally applied compressive load. This observation suggests that although the understanding of compressive response has improved over the last 25 years, this understanding is in a very limited portion of the entire range of possible compression response. In terms of figure 1, all of the reviewed work on compression failure theories fall in the microstructural response block.

GENERAL COMPRESSION RESPONSE
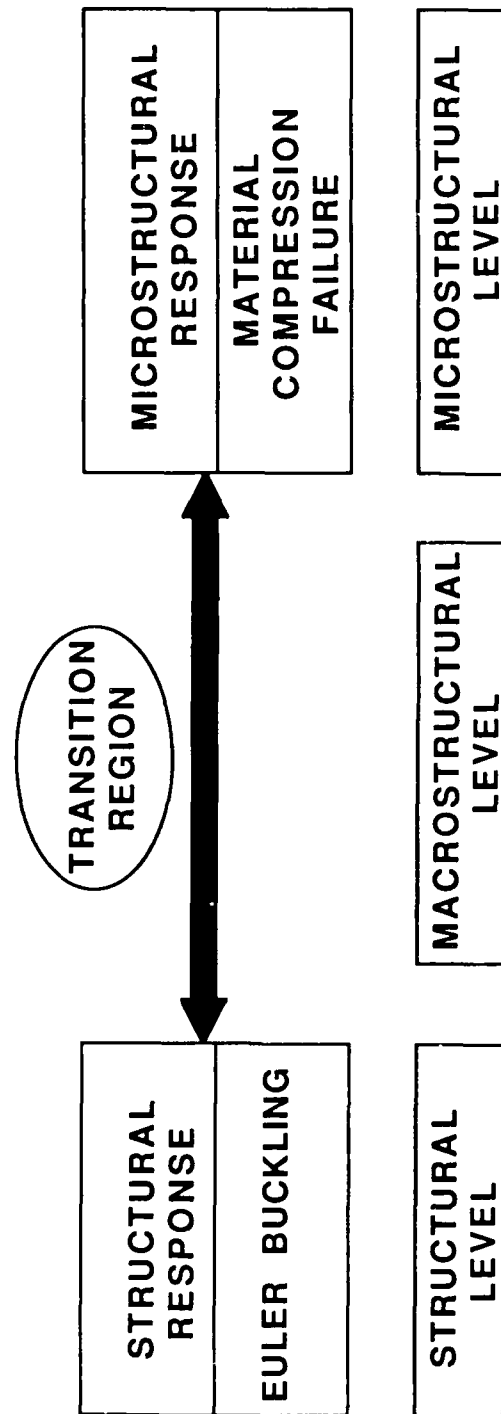
Figure 1: General Compression Response
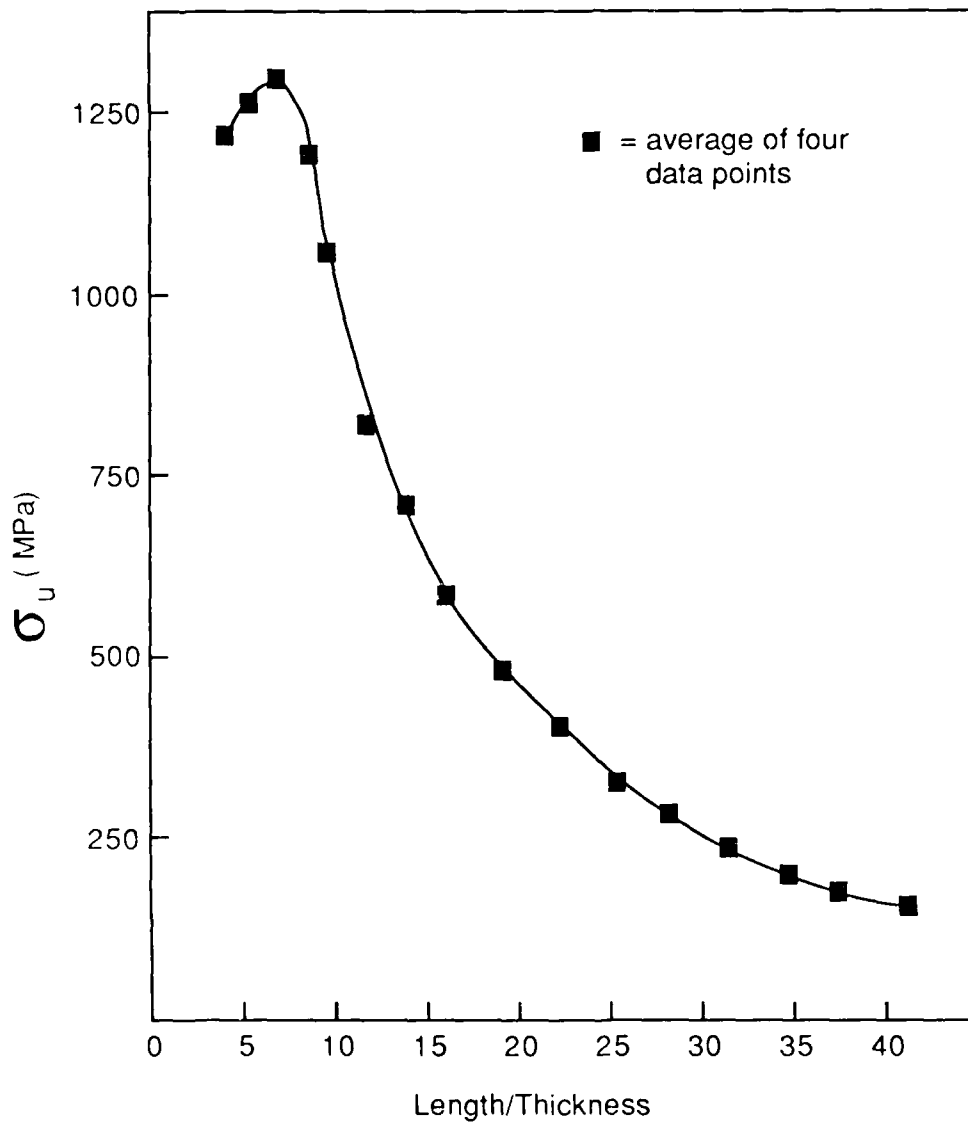
Figure 2: Ultimate Stress vs. Length-to-Thickness Ratio (Smoot [20])
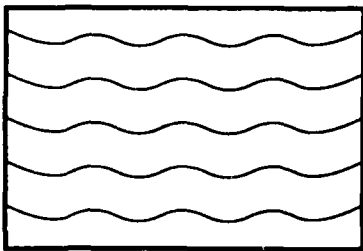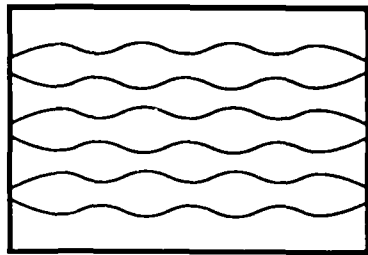
EXTENSIONAL MODE

SHEAR MODE
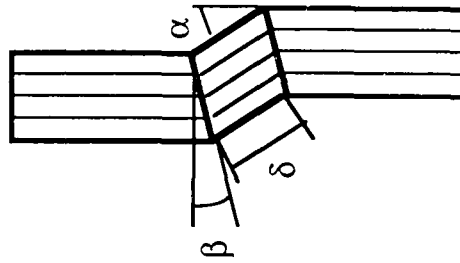
KINK BAND GEOMETRY

Figure 3: Microbuckling Failure Modes and Kink-Band Geometry

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MICROSTRUCTURAL COMPRESSION RESPONSE

Weak Fibers ? / Fiber Failure

Strong Fibers ?

Weak Matrix or Fiber-Matrix Interface ? / Transverse Tension

Strong Matrix ? / Microbuckling

High FVF ? / Shear Mode

Low FVF ? / Extensional Mode

Ideal Composites ? / ~ Shear Modulus

Real Composites ? / Initiated by Voids, Stress Concentrations, Areas of Weak Matrix, Free Boundaries

Compliant Matrix ? / Bending Failure

Stiff Matrix ? / Fiber Kinking
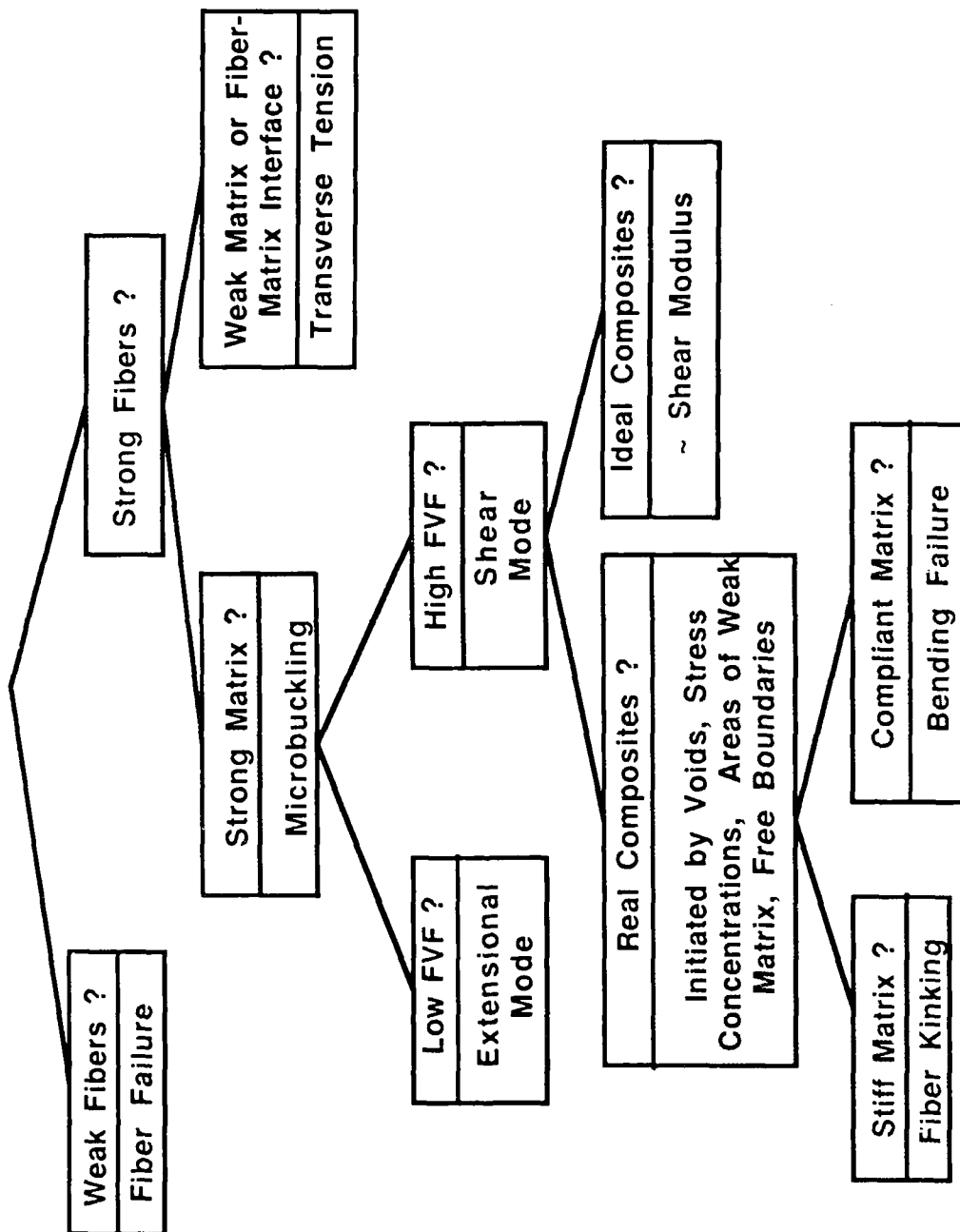
Figure 3. Microstructural Compression Response (FVF is fiber volume fraction)

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TABLE 1: COMPRESSION TEST METHOD EVALUATIONS

Ref	Authors	Fixtures/Specimens Evaluated	Comments
1	Whitney, et al.	Celanese, IITRI, Northrop, NBS, SWRI, Lockheed, Edgewise Sandwich Beam, 4-Point Bend Sandwich Beam	Discussion of compression test methods
2	Abdallah	Celanese, IITRI, NBS, Northrop, SWRI, Lockheed, Wright-Patterson, Rockwell, TEI, Narmco, ASTM D695, Boeing, Fed. Std. 406, RAE, Sandwich Beam	Literature review
5	Adsit	ASTM D695, Celanese, IITRI, Sandwich Beam	Experimental; ASTM round robin results
8	Ciark, et al.	IITRI, Laterally Restrained, Capped End-Loaded	Experimental; 3 thicknesses, 3 widths and 3 laminate orientations tested. No one fixture acceptable for all configurations
10	Hofer, et al.	IITRI	Experimental; Original description and evaluation of ITTRI fixture

TABLE 1: COMPRESSION TEST METHOD EVALUATIONS

Ref	Authors	Fixtures/Specimens Evaluated	Comments
11	Lamothe, et al.	Celanese, IITRI, End-Loaded Cylinders	Experimental; Celanese and IITRI unsatisfactory for metal matrix specimens tested
12	Irion, et al.	IITRI style and Capped End-Loaded Fixtures	Experimental; Fixtures evaluated under static and creep loading
13	Daniel, et al.	101.6 mm dia., 25.4 mm wide, 6-8 ply rings	Experimental; Fixture for high strain rate (20-500 1/sec) testing evaluated
14	Bogetti, et al.	IITRI	Theoretical; reports admissible length-to-thickness ratios considering uniform compressive stress in gage section and buckling stability
15	Reiss, et al.	Specimens subjected to combined compression and bending	Theoretical, reports admissable length-to-width ratios for combined stress to decay to a state of uniaxial compressive stress,

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TABLE 1: COMPRESSION TEST METHOD EVALUATIONS

Ref	Authors	Fixtures/Specimens Evaluated	Comments
16	Rehfield, et al.	Tabbed Shear-Loaded Specimens	Theoretical; Closed form approximate solution for stresses at tab/specimen interface, tab terminations, and in gage section
17	Woolsten-croft, et al.	Celanese, RAE, ASTM D695, Modified Celanese, BAe	Theoretical/Experimental; Finite element analysis used to determine S_{xx}, S_{yy}, S_{zz}, at specimen midlength
18	Shuart	Sandwich Beam	Theoretical/Experimental; 3-D finite element analysis of sandwich beam to determine the effect of the honeycomb core
20	Smoot	IITRI	Experimental; Compressive strength versus gage length reported

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TABLE 2: Compression Test Method Summary

Fixtures	Shear-Loaded Gage Length		End-Loaded Gage Length		Ref
	Supp	Free	Supp	Free	
Celanese		X			6,1
IITRI		X			10,1
Sand Flex	1/2	1/2			1
NASA				X	8
NBS				X	3,1
Rockwell				X	2
Wright Patt				X	2
RAE				X	2
TEI				X	10,2
Narmco				X	10,2
ASTM D695			X		7
Northrop			X		1
Boeing			X		2
SWRI			X		1
Lockheed	1/2		1/2		4

TABLE 3: STATIC COMPRESSION

Ref	Authors	Material	Orientation	Test Configuration	Comments
5	Adsit	E-glass/1002 AS/3501 T300/5208 T300/934	[0]	IITRI, Celanese, D695, Sandwich Beam	All materials tested in all fixtures for D30 round-robin
8	Clark, et al.	T300/5208	[0] [±45] [0/±45/90]	IITRI, End-Loaded (NASA), Face Supported	3 widths and 3 thicknesses tested
10	Hofer, et al.	MOD II/5206, T300/5208, Hercules3002M, Boron/Epoxy	[0], [90], [0/±45/0/90]	IITRI	Tests at 21 C and 177 C dry
11	Lamothe. et al.	T300/5208 S2/SP-250 Kev/CYC. 5143 FP/Al, FP/Mg.	$[0]_{16}$ $[0/\pm 45/90]_{2s}$ $[0/90]_{8s}$ $[0]$	Celanese and ITTRI for all materials and end-loaded cylinders for metal matrix specimens	Celanese and ITTRI unsatisfactory for metal matrix specimens tested
12	Irion, et al.	AS/3501-6 S2/3501-6	$[0]_{25}$ $[90]_{25}$ $[0]_{22}$ $[90]_{22}$	6.4 - 9.5 mm wide, 83 - 90 mm long, capped, end-loaded; 12.7 mm wide. 114 mm long shear loaded	Static and creep data reported

TABLE 3: STATIC COMPRESSION

Ref	Authors	Material	Orientation	Test Configuration	Comments
17	Woolsten-croft et al.	XAS/914C (graphite/epoxy)	[0]	Celanese, RAE, D695	
18	Shuart	HTS1/PMR-15 (Graphite/Polyimide)	[0], [90], [±45], [0/±45/90]	Sandwich Beam	Tests conducted from -157 C to 316 C
20	Smoot	AS1/3501-6	[0]₁₀	ITTRI, 6.4 mm wide, 1.4 mm thick, gage length from 6.4 - 64 mm	Compressive strength versus gage length reported
36	Hahn, et al.	E-glass, T300, T700, P75, Kevlar 49, & FP Alumina fiber bundles in 2 epoxy resins. Laminates shown is ref 40.	Single fiber bundles and [0]	IITRI, and single fiber bundles in epoxy resin blocks	Refs. 35, 40, & 41 report complimentary data

TABLE 3: STATIC COMPRESSION

Ref	Authors	Material	Orientation	Test Configuration	Comments
41	Hahn, et al.	T300 in 5208, BP907, 4901/MDA, 4901/mPDA, PEEK & PPS. T700 in BP907, 4901/MDA, 4901/mPDA. Kev/epoxy & S2-glass/epoxy	[0]	IITRI	Refs. 35, 40, & 41 report complimentary data
42	Sohi, et al.	T300 in 5208, BP907, 4901/MDA, 4901/mPDA. T700 in BP907, 4901/MDA, 4901/mPDA.	[(45/0/-45/90)]$_{3s}$	IITRI	Refs. 35, 40, & 41 report complimentary data
44	Piggott et al.	E-glass, HMS & HTS graphite, Kevlar, all in polyester	[0]	End loaded solid cylinders	Degree of resin cure varied

TABLE 3: STATIC COMPRESSION

Ref	Authors	Material	Orientation	Test Configuration	Comments
45	Piggott et al.	Steel/epoxy	[0]	End loaded solid cylinders	Strength of steel rods varied
47	Sinclair et al.	AS/PR288 T300/5208	[0]	IITRI	
52	Kim	AS/3501-5A	[+15] - [90], [±15] - [90] in 15 degree increments	Dogbone, 13 x75 mm gage length, lateral restraint, thickness not given	Results compared to Tsai-Wu failure theory
54	Potter, et al.	Fibredux 914/XAS (graphite/epoxy)	24-ply laminate, 50% 0° & 50%±45° plies	30 mm wide, 100 mm long, end-loaded, perimeter of gag-section clamped, 4.83 mm holes	Some specimens preloaded, RTD & HW tests
55	Purslow, et al.	Fibredux 914/XAS (graphite/epoxy)	24-ply laminate, 50% 0° & 50%±45° plies	30 mm wide, 100 mm long, end-loaded, perimeter of gag-section clamped. 4.83 mm holes	RTW & HD tests

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TABLE 3: STATIC COMPRESSION

Ref	Authors	Material	Orientation	Test Configuration	Comments
56	Shuart, et al.	AS4/3502	48 ply [±45] style laminates with 0, 8, 17, 25, & 33% 90 plies	127 mm wide, 254 mm long plates, clamped ends simply supported along length, end-loaded	Specimens unnotched and with varying hole sizes tested
57	Knauss et al.	T300/5208	48 and 24 ply (±45, 0, 90) style laminates	127 mm wide, 254 mm long plates, capped, simply supported along length, end-loaded	
58	Guess, et al.	Kev 49 328 Fabric/5209 Kev 49 181 Fabric/5208	$[0/90/±45]_s$ $[0,8,16,24...]$	End loaded solid cylinders, 25.4 mm long, 11.4 mm dia.	Through-thickness compression, void content 1-20 %
59	Leach, et al.	S2/LRF-215* Kev 49/LRF-215 T300/LRF-215 * Brunswick Ep.	[0], [0/90]	38 mm square, 25.4 mm thick "near cubes" from filament wound rings, curved loading blocks	Through-thickness tests
60	Ditcher, et al.	Ciba-Giegy Fibredux 914C-HTS-5	[0/90] [90/0]	5 mm wide, 60 mm long, capped, end-loaded, lateral restraint, 1 & 2 mm thick	0.5 mm x 60 mm, Al end blocks bonded to specimen, lateral restraint, 1 & 2 mm thick

TABLE 3: STATIC COMPRESSION

Ref	Authors	Material	Orientation	Test Configuration	Comments
61	Hayashi	Epikote 828	------	End loaded solid cylinders, 15 mm long, 15 mm dia.	Shear modulus versus compressive stress reported
62	Kar, et al.	AS1/3501-6	$[(+45/90/0)_3$ $(90/0/+45)$ $(+45/0)_5 0_2]_s$	Specimen size and fixture description not given	
63	Walrath, et al.	3-D Carbon-Carbon	3-D Orthogonal	Celanese Northrop ETL Northrop ETL Northrop ETL	Room temp dry Room temp wet High temp dry High temp wet
18	Shuart	HTS1/PMR-15 (Graphite/ Polyimide)	$[0], [90], [\pm 45], [0/\pm 45/90]$	Sandwich Beam	Tests conducted from -157 C to 316 C

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TABLE 4: DYNAMIC COMPRESSION

Ref	Authors	Material	Orientation	Test Configuration	Comments
13	Daniel, et al.	SP288/AS SP288/T300	[0] [90] [0] [90]	Rings, 101.6 mm dia., 25.4 mm wide, 6-8 plies thick, load applied explosively through a liquid	Dynamic compression tests, 20 to 500 sec.$^{-1}$
66	Baldini, et al.	AS/3501-6	39 and 43 ply ($\pm$45/0/90) style laminates	5 different bolted joint compression specimens specific to this program	
67	Highsmith, et al.	AS/3502	$([0/\pm45/90]_s)_6$ $([0/90/\pm45]_s)_6$ $([0/\pm45/90/-45]_s)_6$	25.4 mm wide, 102 mm unsupported gage length, shear loaded	R=10
68	Matondang et al.	T300/914C	$[\pm45]_{8s}$ $[0_2/\pm45/0_2/ \pm45/90]_s$	16 mm wide, 210 mm long shear loaded, lateral restraint	R= -1, influence of anti-buckling guides studied
69	Ramkumar	T300/5208	$[0/45/90/-45]_{8s}$ $[45/90/-45/0]_{8s}$ $[90/45/0/-45]_{8s}$	38 mm wide, 152 mm long 38 mm unsupported gage length, shear loaded	R=10, specimens unflawed and with imbedded delaminations

TABLE 4: DYNAMIC COMPRESSION

Ref	Authors	Material	Orientation	Test Configuration	Comments
70	Mohlin, et al.	T300/1034E, Neat epoxy	$[\pm45/0_2/\pm45/90/0_3/\pm45/0_2]_s$	24 mm wide, 104 mm long 24 mm unsupported gage length, shear loaded, 6 mm holes	R=-∞ Room temp. dry Rom temp. wet
71	Grimes	AS/3501-6	$[0]_{16}$ $[90]_{16}$ $[\pm45]_{4s}$ $[(\pm45)_5/0_{16}/90]_{4c}$	Atmur fixture, 50 mm wide, 200 mm long shear-loaded, lateral restraint	Room temp. dry Room temp. wet High temp. dry High temp. wet
72	Grimes, et al.	AS1/3501-6	$[(\pm45)_5/0_{16}/90_4]_c$ $[(\pm45)_5/0_{14}/90_4]_c$ $[(\pm45)_3/0_{16}/90_4]_c$	Atmur fixture, 50 mm wide, 200 mm long, shear-loaded, lateral restraint	Low temp wet Room temp dry/wet High temp dry/wet
73	Walsh, et al.	T300/5208 T300/5209	$[0_2/\pm45]_{5s}$ $[0/45/0/-45]_{5s}$ $[0/\pm45/90]_{5s}$	25.4 mm wide, 152 mm long, 51 mm unsupported gage length, 6.4 mm holes, IITRI fixture	R=0.1, 10 Hz
74	Han	Fiberglass/polyester	Combination random mat and unidirectional	10.2 mm wide, 10.2 mm thick, 30.5 mm long, capped, end-loaded	Low temperatue fatigue

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